Geophysical Journal International

Geophys. J. Int. (2010) **180,** 552–558 doi: 10.1111/j.1365-246X.2009.04440.x

Seismic activity at Cadamosto seamount near Fogo Island, Cape Verdes—formation of a new ocean island?

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Accepted 2009 October 30. Received 2009 October 13; in original form 2009 May 6

SUMMARY

In global catalogues only a handful of earthquakes occurred at or near the Cape Verde islands. The two most recent events occurring in 1998 and 2004 were observed in the southwest of the Cape Verde archipelago away from aerial volcanic centres. Event relocation suggests that both earthquakes may occur at the Cadamosto seamount, a 3-km-tall submarine volcanic edifice to the southwest of the active volcanic islands of Fogo. Swath mapping efforts revealed numerous small volcanic cones between the volcanic island of Brava and the seamount and between Fogo and Brava. The distribution of volcanic vents may support two plumbing systems, one feeding Fogo and volcanic cones between Fogo and Brava and another system feeding Cadamosto seamount. Using ocean-bottom seismic stations of opportunity, deployed roughly a month after a $m_b = 4.3$ earthquake occurred in 2004 August near or at the Cadamosto seamount, we were able to locate local seismic activity clustering at the seamount. We propose that these events reflect brittle rock failure due to magma redistribution in or near a central magma reservoir or more likely dyke intrusion. The observations reported here suggest that Cadamosto seamount is the seismically most active feature in the archipelago. It might be reasonable to hypothesis that ongoing activity causes the Cadamosto seamount to grow, forming a new oceanic island in the future.

Key words: Oceanic hotspots and intraplate volcanism; Dynamics: seismotectonics; Subaqueous volcanism; Volcano seismology; Atlantic Ocean.

1 INTRODUCTION

The volcanically most active region of the Cape Verde hotspot province is the area around Fogo. The oceanic island Fogo is located in the southwestern part of the Cape Verde archipelago, some 700 km off the coast of Senegal, Africa. The archipelago is of volcanic origin, related to the deep-seated Cape Verde hotspot (Courtney & White 1986; McNutt 1988; Grevemeyer 1999; Holm *et al.* 2006; Pim *et al.* 2008). The Cape Verde islands do not form a linear island chain, but form a horseshoe-shaped group of volcanic edifices. However, they show a weak age progression from east to west, perhaps reflecting the near stationary nature of the African Plate with respect to the underlying mantle (Holm *et al.* 2006). The oldest volcanic rocks occur on Sal and Maio and have been dated with 12 and 16 Ma, respectively. Only Fogo and Santo Antao experienced significant volcanism in the last 500 ka (Plesner *et al.* 2002; Holm *et al.* 2006). Thus, recent volcanism is restricted to the western ends of the northern and southern arms of the Cape Verdian 'horseshoe'. Fogo, however, is the volcanically most active aerial volcano in the archipelago and its aerial apron is entirely covered in young volcanic rocks. Holm *et al.* (2006) hypothesized therefore that the island may be entirely Quaternary in age. In historical times, between 1500 (the arrival of the first settlers) and 1750, Fogo volcano erupted many times from the summit of Pico do Fogo. The edifice rises from a remarkably flat plain caldera floor at ∼1700 m above sea level, the Cha das Caldeiras, to 2829 m. The caldera formed during a sector collapse of Fogo approximately 80 ka ago (Le Bas *et al.* 2007; Masson *et al.* 2008). Thus, the Pico do Fogo formed as a post-landslide volcano in the landslide scar. However, the last intense activity at the summit of the volcano occurred in about 1725 and thereafter, apart from brief, possible phreatic or phreatomagmatic explosions (Day *et al.* 1999), the summit crater of Pico do Fogo has been inactive. Since then, eruptions occurred from fissures on its lower flanks and within the Cha das

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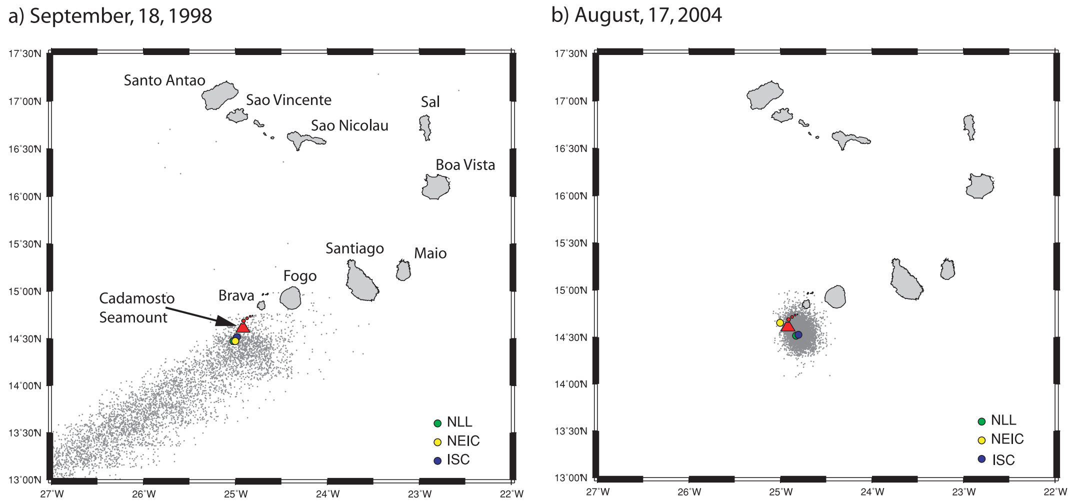

Figure 1. Maps showing the NLL relocation of the (a) 1998 September 18 earthquake and (b) 2004 August 17 earthquake. The NLL location PDF is represented by the gray cloud of points, and the NLL maximum-likelihood solution is shown as a green dot, the NEIC epicentre by yellow dot and the ISC epicentre by the blue dot. The red volcano marks the location of the Cadamosto seamount.

Caldeiras. Historic eruptions occurred in 1769, 1785, 1799, 1847, 1853, 1857 and 1951 (e.g. Day *et al.* 1999) and 1995 (Heleno *et al.* 1999).

The submarine part of Fogo overlaps the adjacent edifice of Brava. No historic eruptions have been reported on Brava, although it is seismically more active. A temporary network operated in early 1994 allowed the detection of volcano-tectonic earthquakes occurring under Brava and under the passage between the islands of Brava and Fogo (Heleno & Fonseca 1999). Recent constraints on event locations based on local seismic stations (Fonseca *et al.* 2003) and hydroacoustic detection techniques support the observations from 1994 that seismic activity occurs mainly halfway between Brava and Fogo (Helffrich *et al.* 2006), a site of seismic activity precursory to the last eruption on Fogo in 1995.

In the last 12 yr two teleseismically detected earthquakes with magnitudes of $m_b > 4$ occurred to the southwest of Fogo and Brava, in the vicinity of the Cadamosto seamount (Fig. 1). One earthquake occurred on 2004 August 17, roughly one month before an active seismic experiment was conducted at Brava and Fogo during the cruise M62/3 of the German R/V *Meteor* (Grevemeyer *et al.* 2004). Seismic stations deployed to record seismic shots detected a number of volcano-tectonic earthquakes. Here, we survey the relationship between large earthquakes detected at teleseismic distances, local earthquake activity and seafloor features revealed by swath-mapping efforts around Fogo and Bava. All recent observations together may suggest that seismic and perhaps volcanic activity is shifting away from Fogo towards the Cadamosto seamount. Thus, the seamount is perhaps going to rise, forming a new ocean island in the future.

2 BATHYMETRIC MAPPING

Multibeam-sonar data collected in the vicinity of Fogo and Brava are from an Altas Hydrosweep swath mapping echosounder (Grant & Schreiber 1990) operated during R/V *Meteor* cruise M62/3 in summer of 2004. The system operated 59 beams within an angle of 90°, surveying a stripe on the seabed with a width about twice the water depth. Data have been processed and edited with the multibeam (MB) Software from the Lamont-Doherty Earth Observatory (Caress & Chayes 1996). The resulting digital terrain models (DTM) have a grid spacing of 100 m × 100 m and were displayed and imaged using the GMT Software (Wessel & Smith 1998).

The slopes of Fogo and Brava are generally smooth (Fig. 2) with a few mounds on the northern flank of Fogo and between Fogo and Brava, interpreted as small volcanic cones. Mounds are largely absent from the southern flank of Fogo, where small canyons dominate the slope topography. Most volcanic cones occur between Fogo and Brava (Fig. 3). Here, Helffrich *et al.* (2006) reported a number of volcano-tectonic earthquakes. The Cadamostro seamount to the southwest of Brava is the most prominent submarine feature in the area. It rises from >4000 m to less than 1500 m water depth. The seamount overlaps with the submarine part of Brava, and a number of small volcanic cones occur between the seamount and the island (Fig. 4). Both the Cadamostro seamount and volcanic cones between Fogo and Brava are likely candidates causing offshore tremor activity recorded on Fogo (Heleno *et al.* 2006).

It is interesting to note that during Fogo's last eruption, satellite-derived interferograms show ground deformation due to a feeder dyke but lack evidence for any volcano-wide deformation related to volume changes of a shallow crustal magma reservoir. Amelung & Day (2002) therefore suggested that Fogo was fed from a relatively deep-seated mantle–lithospheric source. This source may also feed the volcanic vents observed between Fogo and Brava (Fig. 3). However, the fact that Brava did not show any evidence for historic magmatic unrest may suggest that Cadamosto seamount to the southwest of Brava is fed from a different source.

3 RELOCATED GLOBAL SEISMICITY

Small earthquakes reported in global catalogues have generally been located using automated event locations and hence come with large uncertainties due to timing errors, phase mislocation or limitations of the algorithms (Lomax *et al.* 2000). Further, errors associated with the location approach are difficult to trace. We therefore relocated events occurring to the southwest of Fogo using the program NonLinLoc (NLL) (Lomax *et al.* 2000; Lomax 2005). The approach uses efficient global sampling algorithms to obtain an

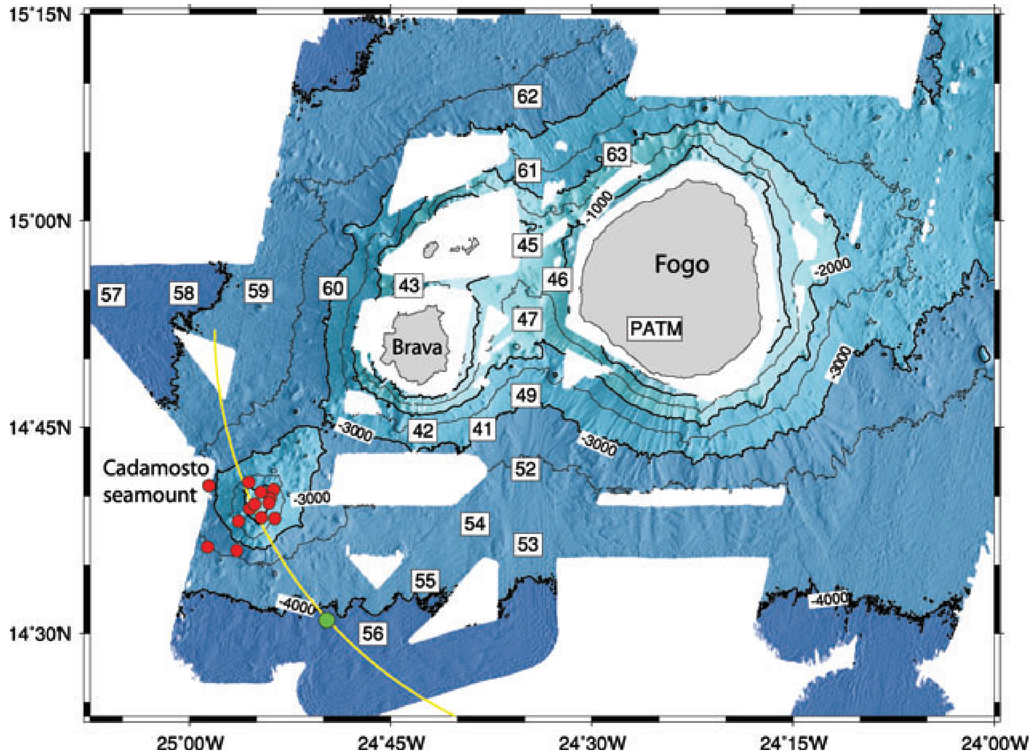

Figure 2. Swath mapping bathymetry from R/V *Meteor* cruise M62/3 of the slopes of Fogo and Brava island and the area with the Cadamosto seamount to the south of both islands. Red dots mark the local earthquakes recorded on the OBS network (white squares with numbers of station name). The green dot is the NLL maximum-likelihood epicentre of the 2004 August 17 event. The yellow line is a sector of a circle around PATM giving the offset between PATM and the earthquake based on *S*–*P* traveltime.

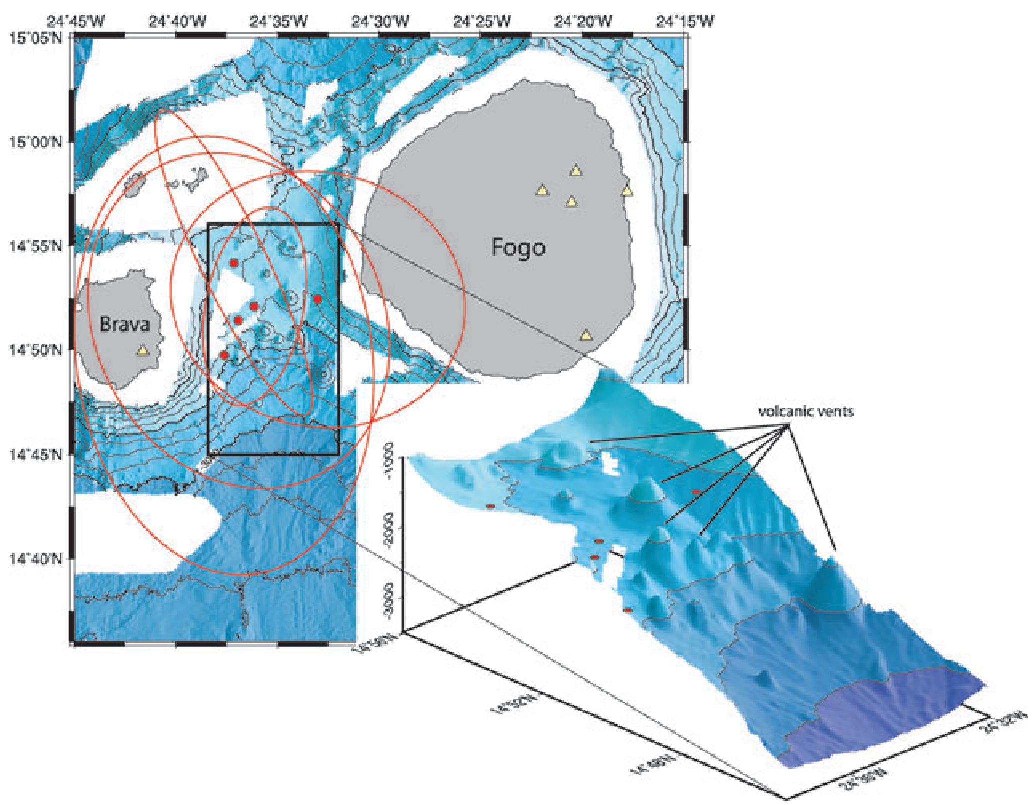

Figure 3. Blow-up of the region between Fogo and Brava. Red dots mark epicentres with error ellipses of earthquakes recorded on local stations between 1999 and 2001 (Helffrich *et al.* 2006). Yellow triangles are seismic stations on Fogo and Brava (Fonseca *et al.* 2003) used for event location. The inset in the lower right shows a perspective view of the bathymetry between Fogo and Brava. Small volcanic cones occurring in the channel may have been the source of offshore volcanic tremor activity (Heleno *et al.* 2006).

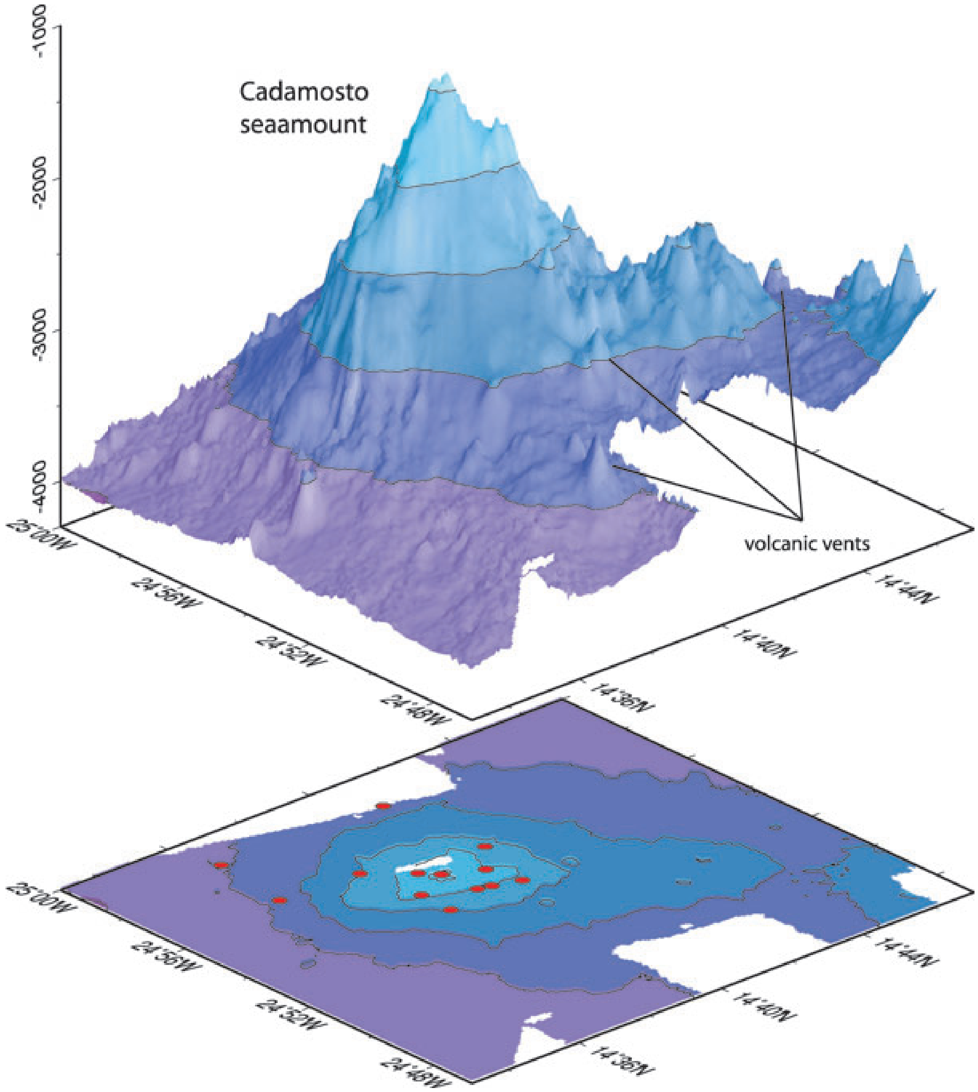

Figure 4. Perspective of the Cadamosto seamount and contour map with epicentres of local earthquakes recorded on the OBS network.

estimation of the posterior probability function (PDF). We relocate the earthquakes using the non-linear oct-tree search algorithm (Lomax *et al.* 2000), providing a complete description of likely hypocentre locations and comprehensive uncertainty information. For determining teleseismic traveltimes, we used the ak135 traveltime model (Kennett *et al.* 1995), representing an optimal spherically layered and hence 1-D velocity model of the Earth.

The first event occurred on 1998 September 18. The International Seismological Centre (ISC) provides a magnitude of $m_b = 4.9$ for the earthquake. Most of the traveltimes reported by the ISC have been provided by North American stations. The resulting PDF has a complicated shape orientated along a southwest–northeast axis, but has a well-defined region of higher probability density that extends from near the summit of the Cadamosto seamount to the south (Fig. 1a). The NLL maximum-likelihood epicentre, the National Earthquake Information Center (NEIC) epicentre, and the ISC epicentre occur roughly 15 km to the southwest of the seamount.

The second event occurred on 2004 August 17. ISC reported its magnitude with $m_b = 4.3$. The PDF is fairly compact and its lobe of high probability density includes the Cadamosto seamount (Fig. 1b). The NLL maximum-likelihood epicentre and the ISC epicentre are ~15 km to the southeast of the seamount; the NEIC epicentre ~10 km to the northwest of its summit. The earthquake was also recorded at the station PATM temporarily deployed on Fogo (Lodge & Helffrich 2006). High quality *P*- and *S*-wave arrival times have been identified at the station. In addition, recordings indicated a number of smaller earthquakes, occurring within 4 min before the main shock hit Fogo, perhaps representing precursors of the main shock (Fig. 5). Furthermore, a number of aftershocks were recorded for roughly 24 hr. *S-P* traveltime at PATM indicates, based on the ak135 model, that the main shock epicentre was located roughly 25 km away from PATM. Both the NLL maximum-likelihood epicentre and the summit of the Cadamosto seamount are located at that distance (Fig. 2), allowing the possibility that the seamount might be the source of the event.

4 OFFSHORE MONITORING OF LOCAL EARTHQUAKE ACTIVITY

Roughly a month after the 2004 August 17 earthquake occurred, we deployed a number of stations around Fogo and Brava, recording

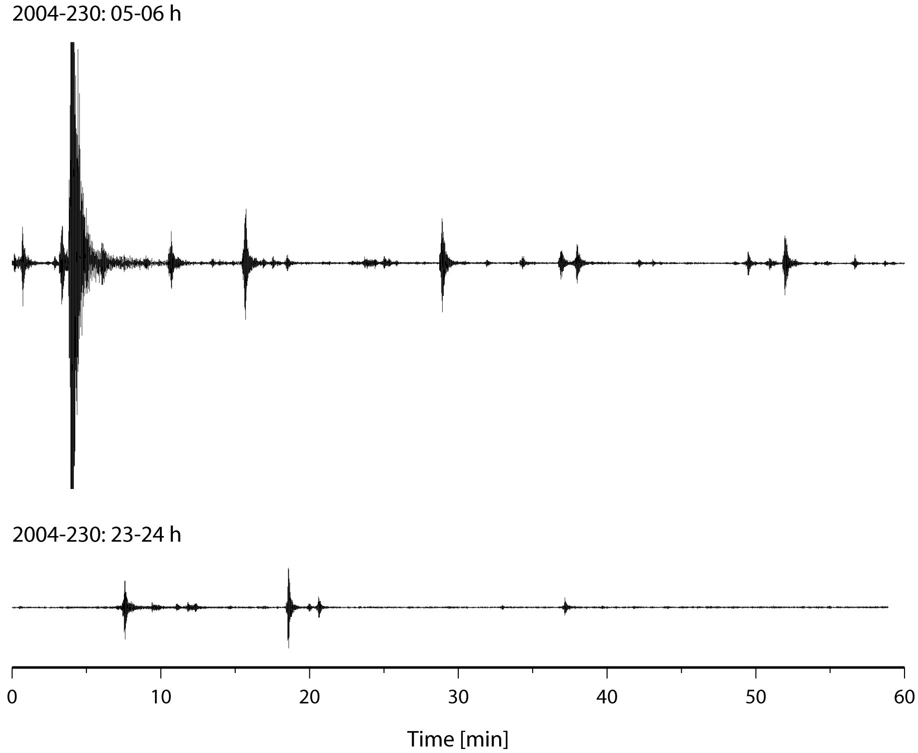

Figure 5. Seismic activity recorded at PATM on 200 4 August 17 between 5 and 6 hr UTC (top panel) and 23–24 hr (bottom panel). Main event arrived at 5:03:48 hr UTC.

active seismic shots fired to yield the crustal structure in the vicinity of Fogo. Stations in the vicinity of the Cadamosto seamount remained on the seafloor for a time period of about 5 d without shooting. Ten additional stations have been deployed on the submarine platform between Fogo and Brava, recording continuously over 11 d without seismic profiling. Within this time we recorded by chance a number of local earthquakes. The largest one occurred on 2004 September 22 and was also sampled on Fogo at PATM. This quake was detected at 16 ocean bottom seismic stations, consisting of both ocean bottom hydrophones and short-period (4.5 Hz) seismometers. In total 12 events were detected. Unfortunately, only one of the earthquakes was recorded at PATM. The moment magnitude of the largest event was estimated with $M_w = 3.5$. To locate the events we used the Joint Hypocenter Determination (JHD) method of Kissling *et al.* (1994). The 1-D velocity model used for the location procedure was based on seismic data obtained using active seismic refraction measurements in the area (Pim *et al.* 2008). The seismic data, however, suggest that seismic structure away from the islands is characterized by typical mature oceanic crust. Thus, we used a seismic model of a 6-km-thick oceanic crust with a high gradient upper crust ($V_p = 4.5$–6.6 km s^{-1}), a low gradient lower crust ($v_p = 6.7$–7.1 km s^{-1}), and a constant upper-mantle velocity of 8 km s^{-1}. To compensate for deviations from the 1-D model, we calculated station correction terms (Kissling *et al.* 1994). The largest corrections were assigned to PATM on Fogo and stations adjacent to the islands, indicating thicker crust under the island. Fig. 6 has examples of waveforms from an event occurring at 04:08 UTC on 2004 September 22. The epicentre of the quake occurs right at the summit of the Cadamosto seamount. All other events cluster at the seamount, clearly supporting a volcano-tectonic nature of the events (Figs 2 and 3). All events have been located with a rms misfits of 0.14–0.65 s in the final JHD location procedure. Formal depths assigned to the events ranges from 0.5 to 15 km below seafloor. However, due to station distribution, uncertainties are too high to be used for interpretation.

5 DISCUSSION AND CONCLUSIONS

Volcano-tectonic events at Cadamosto seamount may be caused by several processes, even though all larger earthquakes are ultimately caused by brittle failure of rock. Brittle rock failure is generally brought about by stresses built up in the volcano by shifting magma or thermal cooling of a magma body (Chouet 1996). It is well known from monitoring active volcanoes that dyke intrusion dynamically modifies the pre-existing stress in the crust, giving rise to ground deformation episodes and seismic events (Rubin *et al.* 1998). A close relation between earthquake swarms, volcanic eruptions, and ground deformation has, for example, been well documented on Mt Etna volcano in the last decade (e.g. Patane *et al.* 2003). Seismic activity precursory to the latest eruption on Fogo in 1995 occurred under Brava and between the islands of Brava and Fogo (Heleno & Fonseca 1999), followed by increased seismicity in Fogo. Heleno *et al.* (1999) argued that seismicity during and preceding the eruption reflected a reactivation of a WSW rift zone after at least several centuries of inactivity. During the *Meteor* M62/3 cruise we deployed 10 ocean bottom hydrophones in the channel between Brava and Fogo. Stations recorded for roughly 11 d before the active source component began. However, we could not identify a single event, while stations recording only for 5 d to the north and east of the Cadamosto seamount identified 12 locatable earthquakes, clustering at the seamount. Further, the two events with $m_b > 4$ reported by the ISC suggest that major seismic activity occurs away from Fogo. However, hydroacoustic monitoring (Helffrich *et al.* 2006) suggests that some activity still issues below the channel, where

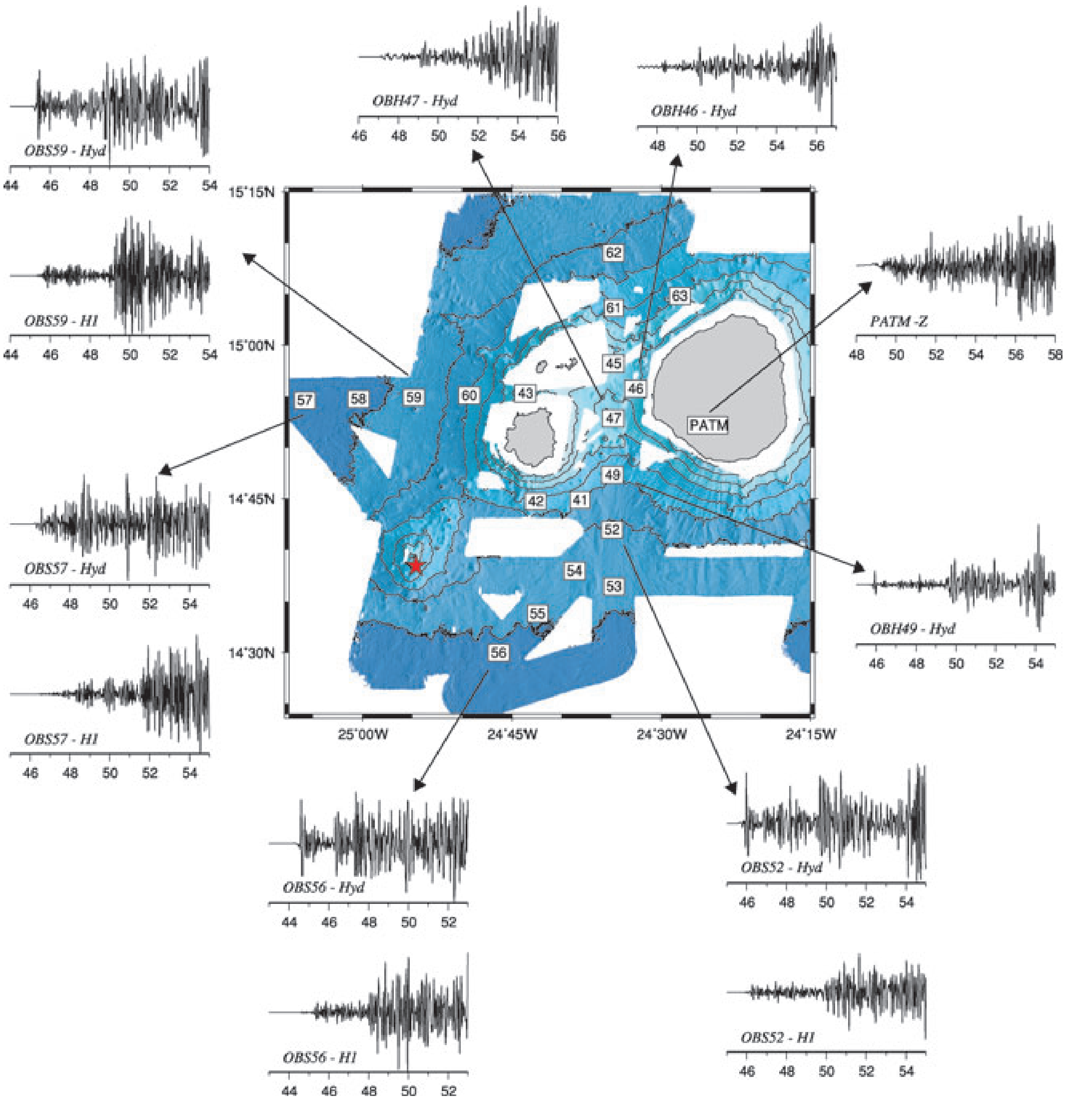

Figure 6. Examples of waveforms recorded on the ocean bottom stations and PATM on 2004 September 22 at 04:08 UTC. Waveforms are from an earthquake with $M_w = 3.5$ occurring at the Cadamosto seamount.

swath mapping efforts detected a number of volcanic cones (Figs 3 and 4). Rocks dredged from the seamounts provided fresh volcanic material (T. Hansteen, personal communication, 2007), suggesting that the features are geologically young and are thus perhaps still active.

Based on seismicity alone it is difficult to detect whether any given feature is volcanically and hydrothermally active or not. Vailulu'u seamount to the west of the Samoa island chain showed seismic activity observed at teleseismic distances in 1973 and 1995. Subsequent sampling and work in the water column clearly suggested that the seamount is hydrothermally active and some rocks were younger than 50 yr (Hart *et al.* 2000). More recent seismic monitoring efforts indicated that the seamount is seismically very active and seismicity is interpreted to be caused by brittle rock failure due to magma redistribution in or near a central magma reservoir (Konter *et al.* 2004). On La Palma, Canary Islands, macroseismic activity occurred as precursor several years before the 1949 eruption (Klügel *et al.* 1999). Between 1936 and 1949, the seismicity focus propagated from north to south, perhaps indicating dyke propagation as a cause.

As for Vailulu'u seamount and La Palma, we believe that seismic activity at Cadamosto seamount indicates magmatic unrest of the seamount. Thus, earthquakes will either be related to the injection or withdrawal of magma in a crustal magma chamber or conduit or be related to dyke intrusion. Earthquakes associated with moving magma have generally small magnitudes and are often linked to volcanic tremors. The fact that two events have been recorded at teleseismic distances suggests that major stresses are caused in the seamount, supporting dyke intrusion. Further, we did not record seismic tremors originating at or near Cadamosto seamount. We therefore favour the interpretation that the occurrence of numerous local events more than a month after a magnitude $m_b = 4.3$ earthquake is related to rock failure caused by dyke injection.

Fogo is discussed to be one of the most volcanically active sites on Earth (Custódio *et al.* 2003; Fonseca *et al.* 2003). However, the observations reported here indicate that future volcanic activity may occur away from Fogo. Interestingly, Cadamosto seamount occurs to the southwest of the archipelago, where with respect to global plate motion the hotspot should be located (Morgan 1983). Thus, we believe that it is reasonable to hypothesis that volcanic activity may shift away from Fogo, forming a new oceanic island at Cadamosto seamount.

ACKNOWLEDGMENTS

The GMT software of Paul Wessel and Walter Smith (Wessel & Smith 1998) was widely used for figure drafting. We are grateful to the Master Kull, officers, and crew of R/V *Meteor* cruise M62/3 for their excellent support at sea. The ISC provided the traveltime data for seismic events occurring on 1998 September 18 and 2004 August 17. This study was funded by the German Science foundation (DFG) through grants GR1964/5–1, and GR1964/7–1. Natural Environmental Research Council (NERC) grant NER/B/S/2001/00315 supported the operation of the seismic station PATM deployed on Fogo. We are grateful to two anonymous referees and the editor Yehuda Ben-Zion for handling our manuscript.

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